Improving Attachments of Non-Invasive (Type III) Electronic Data Loggers to Cetaceans

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LONG-TERM GOALS

The overall goal of this project is to increase the longevity of suction cup attachments for short-term archival tags such as the DTAG.

OBJECTIVES

We are working to extend the routine attachment duration for suction-cup tags to multiple days, if not weeks. In this project we are working to both increase the longevity of short-term archival tag attachments, and to develop quantitative metrics and analysis tools to assess the impact of a tag on the animal. Here we will present: 1) the characterization of the mechanical properties of dolphin skin (*T. truncatus*) under vacuum loading; 2) the development of surface treatments that facilitate adhesive use as an alternative to suction cup attachments; 3) tag body designs that reduce net hydrodynamic loading; and 4) algorithm development and experimental design that enhance fine scale motion analysis for swimming animals.

APPROACH

Our approach is divided into four subtasks:

Task 1: Forces and failure modes in suction cup attachments. Define assays to investigate cup failure modes.

Task II: Assessing the impact of tags and surface attachments on cetaceans. Using Computational Fluid Dynamics we will assess the drag forces created by various suction cup and tag housing combinations.

Task III: Engineered suction cups and surface treatments for improved attachment. In light of Tasks I and II we will engineer suction cups with longer duration using selected materials and molding techniques, cup surface treatments, and investigate the use of adhesives.

Task IV: On-animal performance of engineered attachments and tags. Using free-swimming animals, first in managed facilities and then on released stranded animals and animals tagged at sea, we will attach the engineered system with an instrumented cup to test cup behavior and longevity.

WORK COMPLETED

Task I: Improved material property measurements of skin
Objective: Measure the material properties of skin under vacuum loading and identify the forces that result in cup failure using controlled loading. Building on our previous results we have developed an improved system to measure the material properties of skin under pressure loading. This system uses stereoscopic cameras and digital image correlation to make full-field deformation and strain maps of the skin, in place of the single point measurements made using the SSCUP.

Method: Digital image correlation (DIC) tracks unique features on the surface of material during deformation to extract shape and motion measurements of the substrate. Recently, 3D DIC has been used to capture full-field measurements of deformation over relatively large test areas for a variety of substrates. This technique has been used in ex vivo bulge inflation tests to identify material parameters and perform stress-strain analysis for excised skin. However, there are currently no methodological examples that use DIC to make in vivo measurements of intact skin. We have developed a new portable device that combines pressure loading and DIC (termed here as PDIC) to compare the mechanical properties of skin. Initial testing and validation of the system was conducted on human skin of two subjects. All experimental work was reviewed and approved by the Institutional Review Board (IRB) at the University of Michigan (HUM00091795). Future work will be conducted on animals in human care with our colleagues at Dolphin Quest Oahu.

Task II: CFD modeling for improved tag design
Objective: When attached to an animal, the drag forces acting on the tag can remove the package or adversely affect the behavior or energetics of the animal. As such, it is important to be able to predict the forces generated by the tag in fluid flow. Here we are developing computation fluid dynamics simulations that include both the tag and animal geometry to enable better prediction and understanding of the impact tag forces have on the animal.

Method: To investigate drag effects, we instrumented bottlenose dolphins at Dolphin Quest Oahu with a tag and additional elements to increase drag by enlarging the frontal area of the tag. Building on previous work, we are developing CFD models of the tags used during these experiments to provide an estimate of the additional forces imparted by the tag. CAD models of the tag and simplified surface geometry were first examined in simulation, Figure 1. Simulations were run at multiple speeds (1 to 7 m/s) in steady inline flow. These simulations were used to examine the relative difference in force generation of the increased frontal area over a range of fluid speeds. Next, a simulation of the tag on representative animal geometry in 4 m/s inline flow was performed, and used to examine the relative increase in total drag imparted by the tag to the animal/tag system, Figure 2.

Task III: Engineered suction cups and surface treatments for improved attachment
Objective: We have developed and characterized micro-textures and surface treatments that can be used to improve the adhesive bond between engineered surfaces and cetacean skin. We are now working to combine these engineered surfaces with suction cups into a hybrid glue/suction attachment system, Figure 3.

Methods: A biocompatible cyanoacrylate (Vetbond) has been used to glue micro-textured urethane to a cadaver. The micro-texture both increases the effective surface area and improves the surface wetting properties of the urethane, both of which lead to stronger bonds between the urethane and the glue. Experimental work with dolphin cadavers demonstrated that the bond formed by the glue between the urethane and the skin effectively resisted shear loading, but failed under relatively small forces normal to the attachment surface. Previous work with suction cups indicated that the vacuum force created by a cup is able to resists relatively large normal forces, but the cups start to slide when loaded with relatively small shear forces. On an animal the drag forces created by the tag act as a shear force on the suction cups, and could lead to movement of the tag down and eventually off of the animal's body. This has led to the development of a hybrid glue/cup system, where the adhesion between the cup material and the skin will resist shear loading and the vacuum forces from the cup will resist normal loads.

Task IV: On-animal performance of engineered attachments and tags
Objective: Develop the tag technology and algorithms required to produce quantitative metrics for the assessment of the impact of tags on the animal health and well-being. Specifically, we are working to develop methods that will enable accurate estimates of the power and mechanical work marine mammals use to swim. Mechanical work performed by the animal relates directly to net energetic cost, and these results will be key to improving our understanding of the impact tags have on the animal.
Methods: To estimate increased energetic requirements or behavioral modifications that may result from drag of the tag package, we have developed the hardware, software algorithms, and experimental setup to enable enhanced fine scale motion analysis of swimming animals. A full set of inertial sensors (three axis accelerometers, magnetometers, and gyroscopes), were attached to managed bottlenose dolphins at Dolphin Quest (DQ) Oahu. During the trials the animals were asked to swim with the tag and the tag with additional drag elements. The animals maintained a relatively constant speed by following a remote controlled boat that was driven at a controlled speed. The algorithms developed and applied in this work provide an improved estimate of animal orientation and inertial accelerations over current techniques. Additionally, the constraints imposed on the animals during the experiment enable accurate estimates of the work and power generated by the animals during the steady state swimming tasks.

RESULTS

Task I: Improved material property measurements of skin

Peak displacements increased with increasing peak load, and hysteresis was evident during unloading for all trials at both sites. The energy dissipated during each cycle was quantified using the area within each hysteresis loop and was present during all loading conditions. Figure 4A compares the load-deformation curves from the two sites for one subject at similar loading conditions. Both peak skin displacement and energy absorption were further characterized with linear fits. Peak out-of-plane skin displacements and the energy dissipated over each cycle increased linearly with force for the skin at both the abdomen and the upper back. Figure 4B illustrates the linear relationship between peak force and peak displacement. The r-squared value of the abdomen fit was 0.893 while the fit for the upper back fit was 0.710. While both are relatively good fits, data from the upper back differed more between the two subjects. Figure 4C presents the energy absorbed by the skin as a function of peak force. The r-squared value for the abdomen fit is 0.948 while that for the upper back fit is 0.839. Similarly, data for the upper back differed more between the two subjects, resulting in the lower r-squared value. Both figures present data from the two subjects at both sites.

Task II: CFD modeling for improved tag design

The increased frontal area increases both the drag and lift forces generated by the tag. At 4 m/s the tag+2 increases the drag on the simplified geometry by a factor of about eight from 5.5 N to 44 N, and the tag+4 configuration increases drag by a factor of fourteen (from 5.5 N to 77 N). Adding the tag geometry to the model of the dolphin increased the overall drag of the combined system by less than 2% in 4 m/s in line flow.

Task III: Engineered suction cups and surface treatments for improved attachment

We have fabricated a prototype hybrid suction cup for testing and evaluation. The system consists of a shallow neoprene suction cup with an array of internal feet with super wicking micro textures and chemical surface treatment. Glue is first applied to the feet and then suction will be used to secure the cup to the attachment surface. The suction force will first hold the surfaces together as the bond sets. Applied loads at the attachment site will then be resisted by the suction cup in the normal direction and by the glue in the shear direction.

Task IV: On-animal performance of engineered attachments and tags

Representative data from an animal during an RC boat following task for both the tag and tag+2 conditions, Figure 5. The estimates are broken up into the generally positive thrust power (top plot) and the negative power created by the drag force acting on the animal as it moves through the fluid (middle plot). The positive and negative components of the work performed by the animal are found by integrating the thrust power curves, and the negative drag work that the animal must overcome was found by integrating the drag power curves (bottom plot). These estimates show that the when swimming with the tag+2 configuration the animal had to perform slightly more positive work to overcome the additional drag created by the tag.

IMPACT/APPLICATIONS

Task I: Improved material property measurements of skin

The verification of the system performance using human skin was successful. The PDIC system enables the capture of full-field in vivo deformation of skin under pressure loading. Future work will involve the use of this approach to characterize skin properties at multiple sites for dolphins in human care.

Task II: CFD modeling for improved tag design

The simulation results indicate that the elements used to increase the drag acting on the animals during the experimental Dolphin Quest trials will significantly increase the tag-induced drag. As one might expect, the simulations indicate that bluff elements used to increase the cross-sectional area of the tag create large areas of fluid damming (high pressure in front of the tag) and stagnate flow behind the tag (low pressure behind the tag). This pressure differential acting over the large cross-sectional area results in the intended increased in drag forces. The combined model of the tag and dolphin will be used to provide a more accurate prediction of the increase tag created by the tags worn by the dolphin quest animals. Simulation results from the combined model with the tag+2 and tag+4 elements will be used to provide an estimate of the relative increase to total animal drag created by the experimental conditions.

Task III: Engineered suction cups and surface treatments for improved attachment

The hybrid system will combine the advantages of the of both attachment methods: cups to resist normal forces and glue to resist shear forces. Experimental trials first with a cadaver and then with animals in human care will be performed to test and validate this approach. The cadaver trials will enable controlled testing to failure or with both treated and untreated cup feet, and the on animal trials will be an important first step in the demonstration of this prototype as a viable attachment method for free swimming animals.

Task IV: On-animal performance of engineered attachments and tags

Increasingly, accelerometer measurements are used to infer the energetic cost of activities via proxies such as Overall Dynamic Body Acceleration (ODBA). Here we use information from a full set of inertial measurements and a constrained experimental setup to make estimates of per-stroke mechanical work and power. The power generated by the animal and the resulting mechanical work are important components of total animal energy expenditure. Accurate estimates of these parameters will enable a more complete understanding than parameters derived from accelerometers alone. Further, we apply these mechanical work estimates to quantify the effect of increased tag drag on the animals in these experiments.

REFERENCES

1. Nightingale K, et al. Ultrasound in Medicine and Biology 28, 227-335, 2002
2. Tonge T, et al. Acta Biomaterialia 9, 5913-5925, 2013
3. Viidik A, Journal of Biomechanics, 1, 3-11, 1968

PUBLICATIONS

The following abstracts were accepted for the 21st Biennial Conference on the Biology of Marine Mammals in San Francisco, USA, December 2015.

Title: Metabolic effects of added drag on instrumented bottlenose dolphins

Authors: Julie van der Hoop, Andreas Fahlman, Alex Shorter, Julie Rocho-Levine, Micah Brodsky, Tom Hurst, Michael Moore

Biologging tags add drag to swimming animals. Understanding how increased drag affects individuals' behaviour, metabolics, and kinematics is critical for improving tag attachment, refining tag design and dimensions, and increasing awareness of the impact of tagging on study animals. To investigate drag effects, we instrumented bottlenose dolphins at Dolphin Quest Oahu with a tag and additional drag elements to increase the frontal area by factors of four (tag+4) and eight (tag+8). We compared individuals' measured metabolic rates and behaviours during three tag conditions (tag, tag+4, tag+8) and an un-instrumented control (no tag) while performing a prescribed swimming task. During the task, the animals swam continuously for ~10 min at a self-selected pace (n = 4 individuals), or for ~5 min at a pace (~3 m/s; n = 2) set by following a remote controlled (RC) boat. Average lap times were significantly longer for the tag+8 condition, but did not differ between any other self-selected or RC boat trial conditions. When swimming at self-selected speeds, individuals showed no detectable increase in metabolic rate with increasing experimental drag conditions. When swimming speed was constrained using the RC boat, the effect of exercise on oxygen consumption increased between the control and tag conditions. There was no observed metabolic effect with further increases in drag (tag+4), although individuals increased relative distance from the RC boat and swim speed variability in these trials. These results demonstrate that there may be an energetic cost associated with the added drag from even a reasonably small hydrodynamic tag, and illustrates the importance of the experimental design for these types of metabolic experiments.

Title: Estimating the per-stroke work of a bottlenose dolphin (*Tursiops truncatus*) during a continuous swimming task
Authors: K. Alex Shorter, Lauro Ojeda, Julie Rocho-Levine, Julie van der Hoop, Mark Johnson, and Michael Moore

Movement behaviour of marine mammals is typically studied with tags that measure acceleration at a point on the body. Increasingly, these measurements are used to infer energetic cost via proxies such as ODBA. While proxies based only on acceleration have been shown experimentally to correlate with energetic cost for some activities, the physical justification is weak, making it unclear how to extrapolate these methods to behaviours and species that cannot be tested in the laboratory. Improved, physically based, estimates of work would provide a more complete picture of swimming biomechanics and offer improved insight into energy expenditure. Here we develop a new algorithm to combine data from animal-attached accelerometers and gyroscopes to estimate the mechanical work on the body during swimming. While estimates of body work do not capture peripheral work at the peduncle and flukes, it is an indicator of overall work and provides a direct physical estimate of a key component of energy expenditure. To demonstrate the approach, we performed experiments at Dolphin Quest Oahu with a bottlenose dolphin (*Tursiops truncatus*) trained to follow a GPS-equipped remote controlled boat while instrumented with a tag and drag elements. Inertial tag data and estimates of the animal's swimming speed were used to estimate the power and resulting work needed to follow the boat. Here we present preliminary results from an animal with the tag and the tag plus elements that increased drag by roughly fourteen in simulation. During both trials, the animal swam continuously for 5 min while the boat traveled at an average speed of 3.1 m/s. Added drag elements increased positive (23%) and negative (36%) per-stroke work as more thrust was needed to overcome increased drag during the task. These results are an important step towards determining cost of locomotion and of responses to disturbances of free-swimming cetaceans.

The following abstract was presented at the 39th annual meeting of the American Society of Biomechanics Columbus, OH, August 2015.

Title: Full field in vivo characterization of skin deformation under pressure loading
Authors: W. J. Bong, S. Daly, and K. A. Shorter
Introduction

Skin is the largest organ in the body. It plays an important role in the sensory system and is vital for thermoregulation. This multirole functionality is maintained all while providing a critical line of defense against the external environment. In general, the detailed characterization of skin's mechanical properties facilitates a better understanding of the tissue and advances fields such as disease diagnosis [1], tissue modeling, medical device design, cosmetics, and surgery. Full field deformation and strain measurements are key for the characterization of this viscoelastic composite. However, experimental techniques that provide these types of measurements for skin in vivo are currently lacking.

Digital image correlation (DIC) tracks unique features on the surface of the material during deformation to extract shape, deformation and motion measurements of the substrate. Recently, 3D DIC has been used to capture full-field measurements of deformation over relatively large test areas for a variety of substrates. This technique has been used in ex vivo bulge inflation tests to identify material parameters and perform stress-strain analysis for excised skin [2]. However, there are currently no methodological examples that use DIC to make in vivo measurements of intact skin. In this work, a portable device that combines pressure loading and DIC (termed here as PDIC) is used to compare the mechanical properties of skin at two different sites on the body.

Methods
The experimental setup (Figure 6) consists of two cameras rigidly mounted to a sealed housing that is evacuated using a venturi vacuum pump. The pump creates a partial vacuum in the housing while a pressure sensor logs pressures inside the housing at 20Hz. The housing is made up of four main components – a machined nylon cap; printed ABS camera supports; a machined main PVC cylinder; and a silicone lip. The silicone lip provides a compliant interface and enhances the seal between the cylinder and the tissue. Each camera assembly is comprised of a camera lens (3.5 mm focal length, aperture range of f/2.4 to f/8) attached to a 1.3 megapixel monochrome USB digital video camera. The camera setup provides a near limit for depth of field of about 2 in from the cameras. Quartz glass inserts are set between the camera lens and the nylon cap to protect the lens and provide a good vacuum seal. Illumination for the cameras is provided by LED lights seated in a groove cut in the PVC housing.

The PDIC system was used to characterize the deformation response of skin from two test subjects at two anatomically distinct sites – the abdomen and the upper back between the shoulder blades. Data presented here were collected from two male test subjects: 29.5 (s.d. 7.8) years old, 72.0 (s.d. 4.3) in tall, and weighed 153 (s.d. 8.7) pounds. In this work the unique features for the DIC technique consisted of a speckle pattern printed onto temporary tattoo paper. Following preparation and cleaning of the sites, speckle pattern tattoos were applied and allowed to dry before testing.

The cameras were calibrated with a 12x9 grid before the start of each experiment. A preprogrammed cyclic loading pattern was used to apply pressure loading over a range of forces to the tissue. Each loading condition lasted for 30 s, and a set of preconditioning cycles of the same magnitude and duration were applied before data were collected. Maximum pressure was kept below 0.1 bar (73 N) for the abdomen and 0.12 bar (96 N) for the upper back. These limits ensured that the subjects did not experience discomfort as a result of the pressure loading. During the trials, pressure data was used to control the pump to achieve the desired loading profile. Images of the skin were captured using Correlated Solution's Vic-Snap 2012 software, at about 7 FPS, after the preconditioning phase. Images were analyzed using Correlated Solution's Vic-3D software to obtain full-field displacements, which were in turn analyzed using MATLAB.

Results and Discussion

The shape of the average response obtained in our experiments agrees with load-deformation curves for collagenous tissues [3]. Peak displacements increased with increasing peak load, and hysteresis was evident during unloading for all trials at both sites. The energy dissipated over at each cycle was quantified using the area within each hysteresis loop and was present during all loading conditions. Figure 4A compares the load-deformation curves from the two sites for one subject at similar loading conditions. The anatomy under the skin at the two sites was very different, and this significantly affected the resulting measurements. Soft tissue below the skin at the abdomen resulted in larger deformations and more energy absorption during the cyclic loading, resulting in more gradual and fatter curves for the abdominal data (Figure 4A).

Both peak skin displacement and energy absorption were further characterized with linear fits. Peak out-of-plane skin displacements and the energy dissipated over each cycle increased linearly with force for the skin at both the abdomen and the upper back. Figure 4B illustrates the linear relationship between peak force and peak displacement. The r-squared value of the abdomen fit was 0.893 while the fit for the upper back fit was 0.710. While both are relatively good fits, data from the upper back differed more between the two subjects. Figure 4C presents the energy absorbed by the skin as a function of peak force. The r-squared value for the abdomen fit is 0.948 while that for the upper back fit is 0.839. Similarly, data for the upper back differed more between the two subjects, resulting in the lower r-squared value. Both figures present data from the two subjects at both sites.

Conclusion

The PDIC system enables the capture of full-field in vivo deformation of skin under pressure loading. Future work will involve the use of this approach to characterize skin properties at multiple sites for a range of age groups. We will also explore the use of this device for medical device design and disease diagnostics.

Manuscripts in Preparation:

Title: From the track to the ocean: using flow control to improve marine biologging tags
Authors: Fiore *et al.*

Title: A day in the life of a dolphin: using bio-logging tags for improved animal-health and wellbeing
Authors: Shaio *et al.*

Title: Development of a method to measure in-vivo deformation of skin under pressure loading using digital image correlation
Authors: Bong *et al.*

Title: In-vivo measurement of soft tissue with applications towards quantifying mechanical properties of marine mammal skin
Authors: Shorter *et al.*

Title: Drag loading from experimental bioogging tags assessed with CFD, inertial sensors and metabolic measurements
Authors: Shorter *et al.*

Title: Individual responses to added drag from increasing sizes of biologging tags
Authors: van der Hoop *et al.*

Title: Hydrodynamic drag of gliding bottlenose dolphins wearing biologging tags
Authors: van der Hoop *et al.*

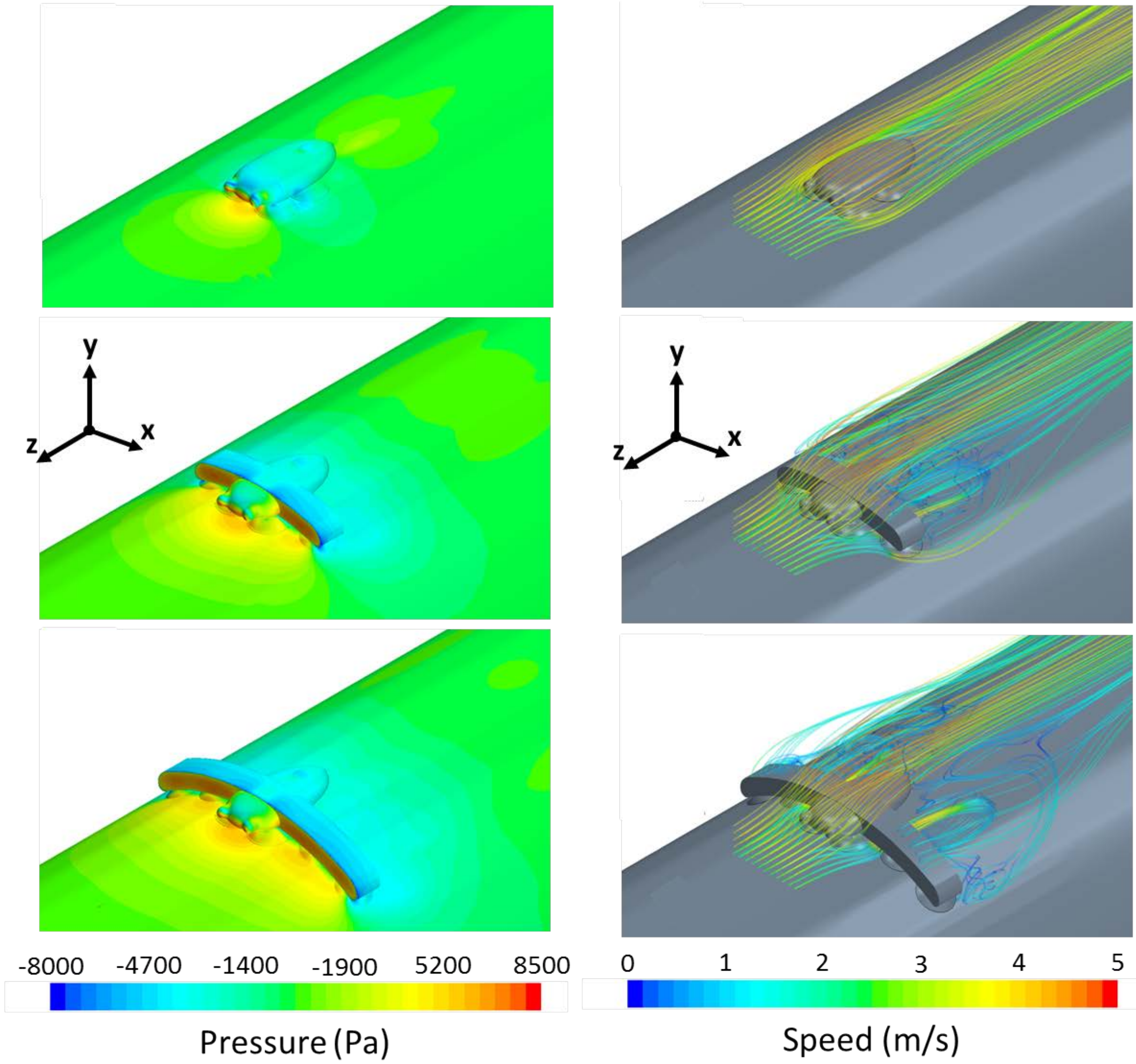

Figure 1. CFD simulation results of the DTAG (top) and additional drag elements used to increase the frontal area by factors of two (tag+2, middle) and four (tag+4, bottom) in 4 m/s inline flow. Pressure is mapped to the surface geometry and is shown on the left, and stream lines with the corresponding fluid speed are shown on the right.

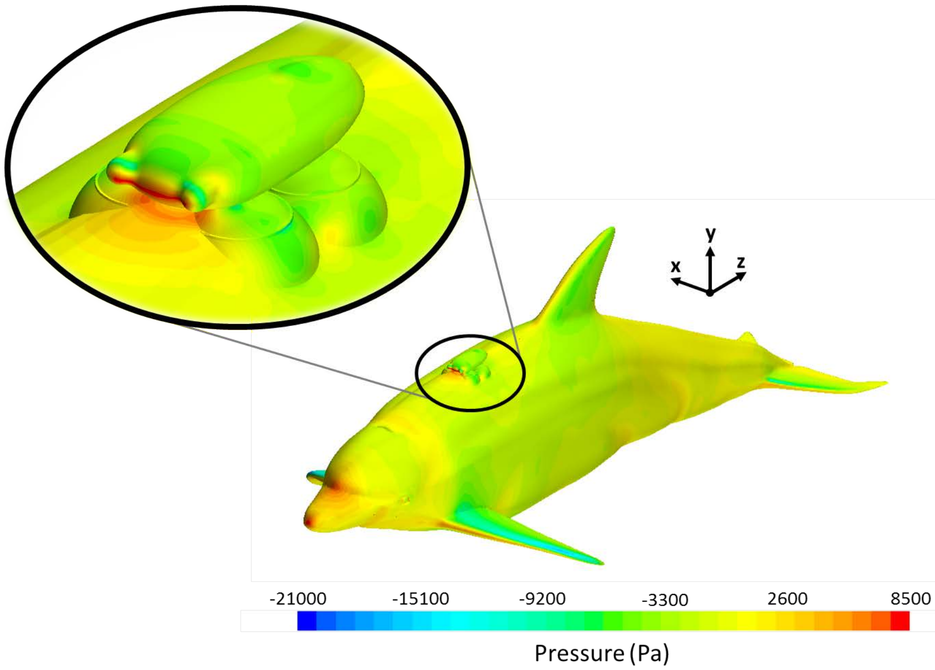

Figure 2. CFD simulation results of the DTAG and representative dolphin geometry in 4 m/s inline flow. Pressure is mapped to the surface geometry with high pressure (slow moving fluid) shown in red and low pressure (fast moving fluid) colored in blues and greens.

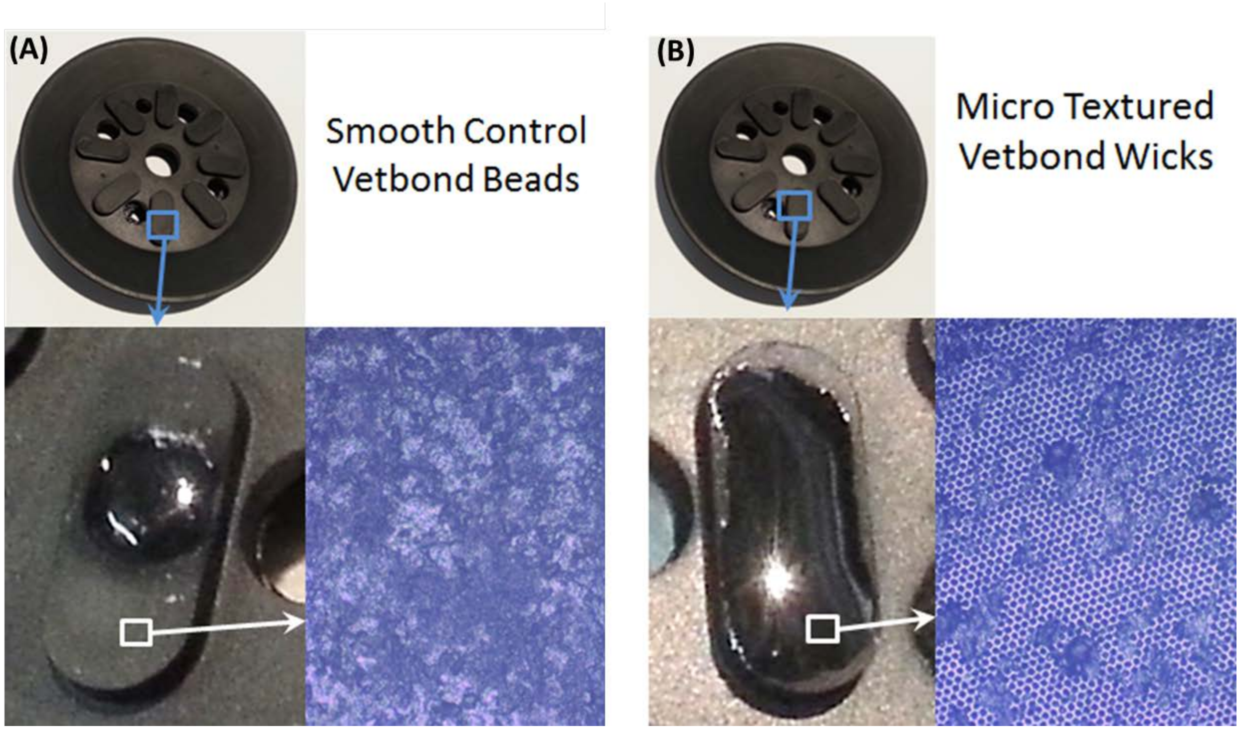

Figure 3. The proposed hybrid suction cup shown (A) without micro-texturing and (B) with micro-texturing. The improved wetting properties imparted by the texturing are shown in the figure details. A droplet of glue placed on the untextured surface has does not spread (bottom left), while the droplet on the textured surface spreads to the edges of the feature (bottom right).

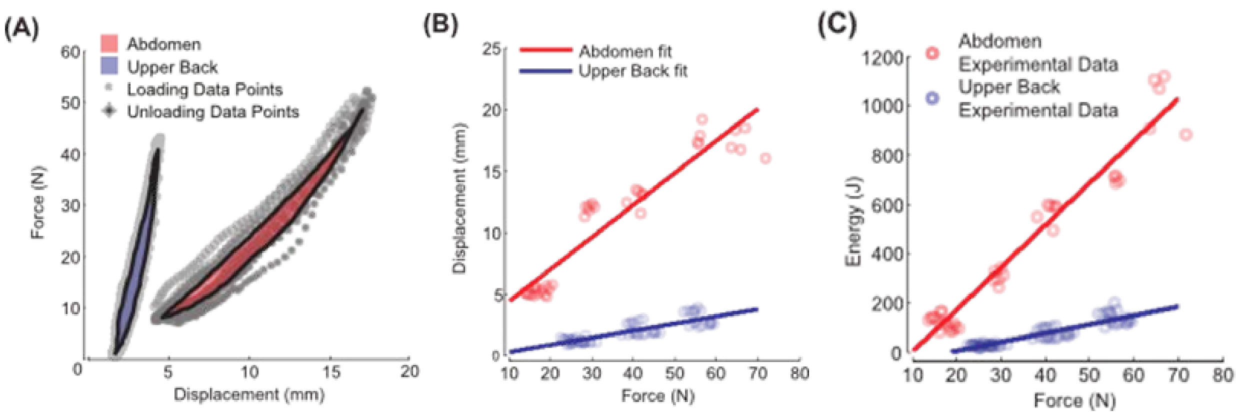

Figure 4: Force-Displacement curve of data from the two sites for one subject and linear fits to experimental data shown. (A) Force-Displacement curve of data from the back is narrower and steeper. (B) Experimental data from both subjects used in the linear fits. Skin on the abdomen exhibits greater displacements for the same pressure. (C) Experimental data from both subjects used. The skin in the abdomen area dissipates more energy than the skin on the upper back.

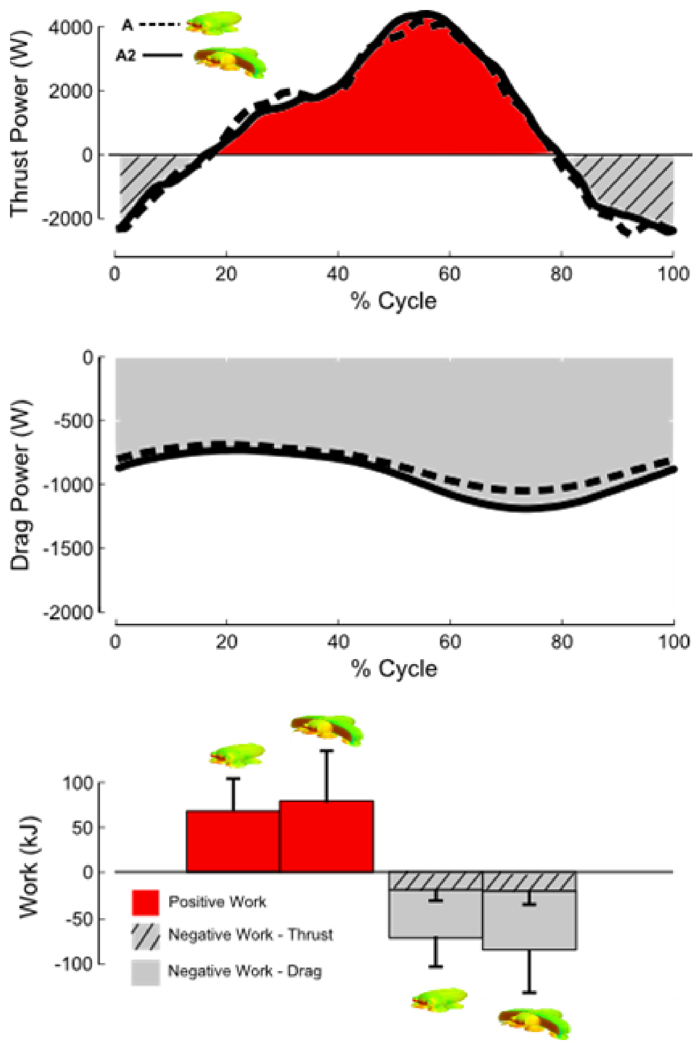

Figure 5 Representative estimates of the average per-stroke work and power calculated from tag data during a steady state swimming task. The top plot is an estimate of the positive and negative power generated during thrust. The middle plot illustrates the negative power created by drag acting on the animal. The bottom plot compares the positive and negative work that the animals generated during the task with the two tag conditions.

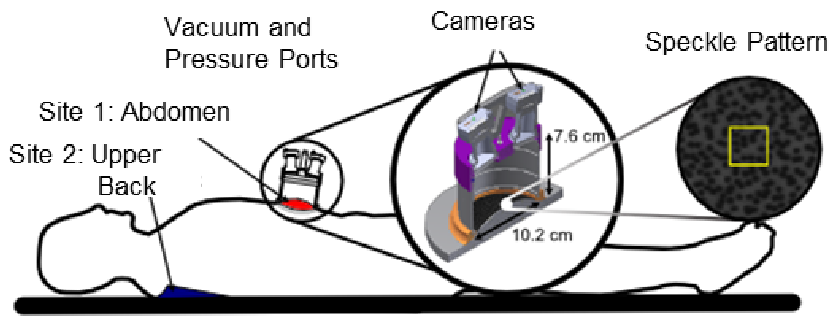

Figure 6 Experiments were conducted on the skin over the abdomen and on the upper back between the shoulder blades. The yellow box shows a representative subset size.